Control Strategies and Algorithms

Adept Systems Inc.

August 2004

Agenda

- Survivability and Automation
- Survivable Networks
- Project Examples
  - Component Level Intelligent Architectures (NSWC-CD Chilled Water Test Platform)
  - NRL DC-ARM Program
  - Network Fragment Healing (ONR Afloat Laboratory)
  - Autonomic Fire Suppression System
- What's Next?
- Summary

Elements and Applications

- Survivable automation infrastructure elements
  - Automation network: media, sentinels, routers
  - Network power
  - Attached automated systems: Controllers, sensors, actuators
  - Attached automated systems power
- Applications
  - Damage assessment, control
  - Auxiliary automation
  - Monitoring and security (anti-terrorism)
  - Condition based maintenance (service after sale)
  - Chem-Bio Attack
  - Self-Healing Buildings ("immune systems for buildings/ships)

Automation Infrastructure Attributes

1. Scope = ubiquitous.
   - The infrastructure must include everything from the component level up through all the ship's subsystems, systems, operations, and off-ship support.
2. Access = transparent, peer-to-peer, global, & secure.
   - Transparency means that communication over the automation infra-structure's network is invisible to the application, that is, the overhead associated with network use is minimized.
   - The combination of peer-to-peer and global means that any given node can exchange information with any one node if so desired.
   - Secure means that all relevant information, sensor, control, & parametric data for each component are made available at appropriate levels of security.
3. Structure = flexible.
   - The infra-structure must be scaled, extended, and adapted to different applications over space and time.
4. Reliability = dependable.
   - Accurate media and network services must be continuously available at acceptable latencies.
5. Cost = affordable.
   - The different attributes must be implemented in a highly cost effective manner. Reduced manning will only come at very high levels of automation with potentially thousands of nodes.
6. Survivability = robust.
   - Must be capable of continued operation at sufficient levels of performance despite damage and casualties induced by stress from shock, blast, fire, and flooding.

Fundamental Problem

- Commercial off the shelf approaches to automation infra-structures usually achieve some combination of attributes (1) - (5).
- What is unique to Naval applications is attribute (6), survivability. While many technology choices exist that may be able to provide attributes (1) - (4), the major difficulty in achieving a suitable automation infra-structure for Navy ships is providing both attributes (5) and (6), that is, affordability and survivability. Survivability is the major cost factor.
- Consequently, the key to the solution is in finding ways to achieve more cost-effective survivability.
- Survivability has been defined to consist of three aspects as follows: susceptibility, vulnerability, and recoverability. Cost effective survivability comes from a judicious implementation of these aspects.

Survivable Networks

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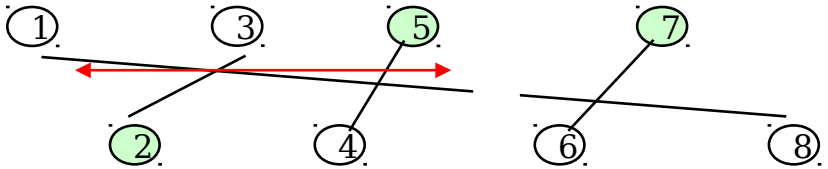
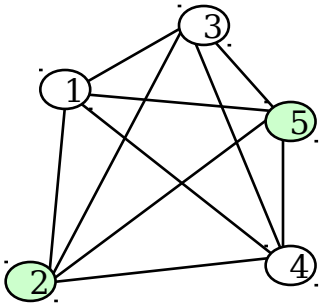
Network Topologies

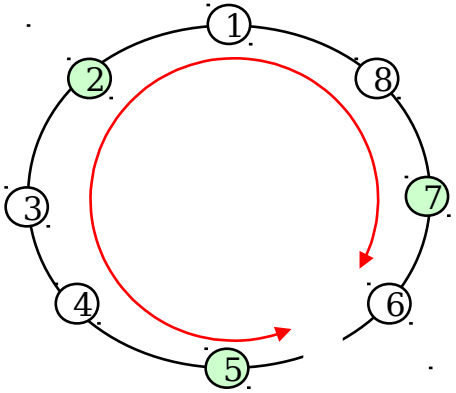
BUS Single Point Failure Susceptible



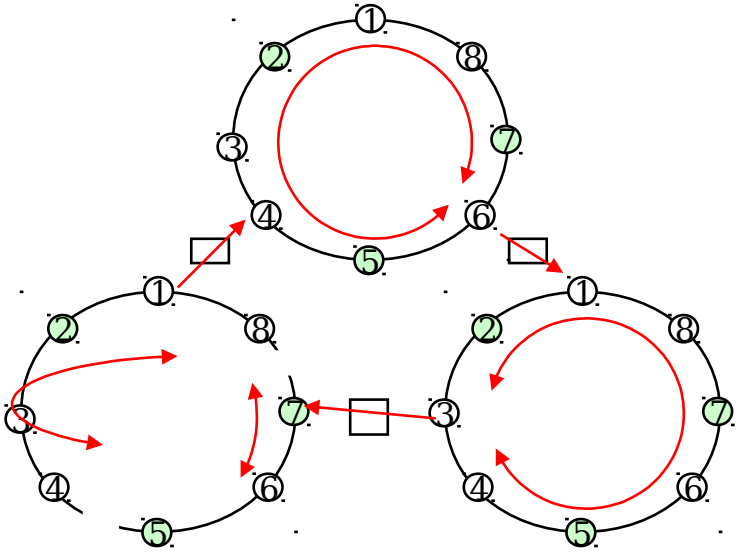
MESH Multiple Point Failure Tolerant
Not Scalable



RING Single Point Failure Tolerant



HYBRID Multiple Point Failure Tolerant
Scalable



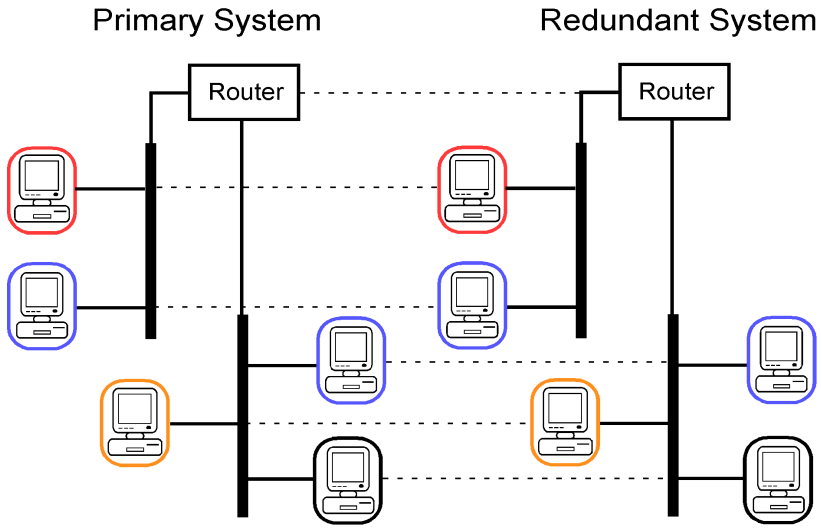
Fault Tolerance Redundancy Schemes

xN Redundancy: Copies of the System

2N : 1

System Copy

- Simplified fault management protocol
- Inherently Unscalable
- Cost Factors Scale Non-linearly with x
- Connectivity Problems

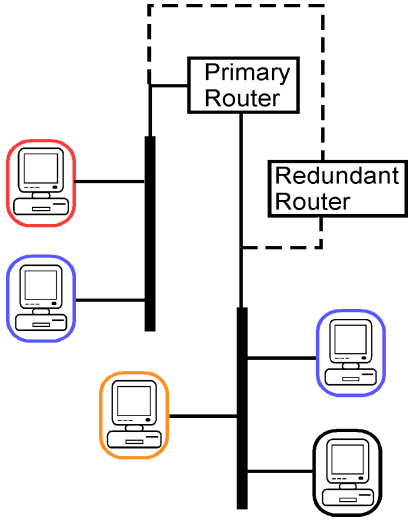


N+m Redundancy: Reconfigurable Critical Copies

N + 1:

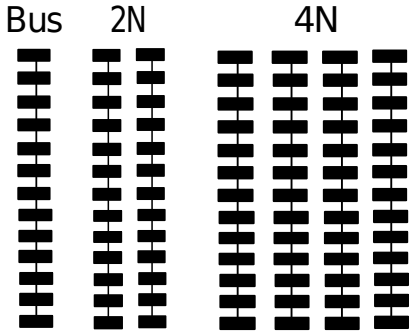
Router Backup

- Robust fault management protocol
- Scale logistically with network
- Scale economically with network

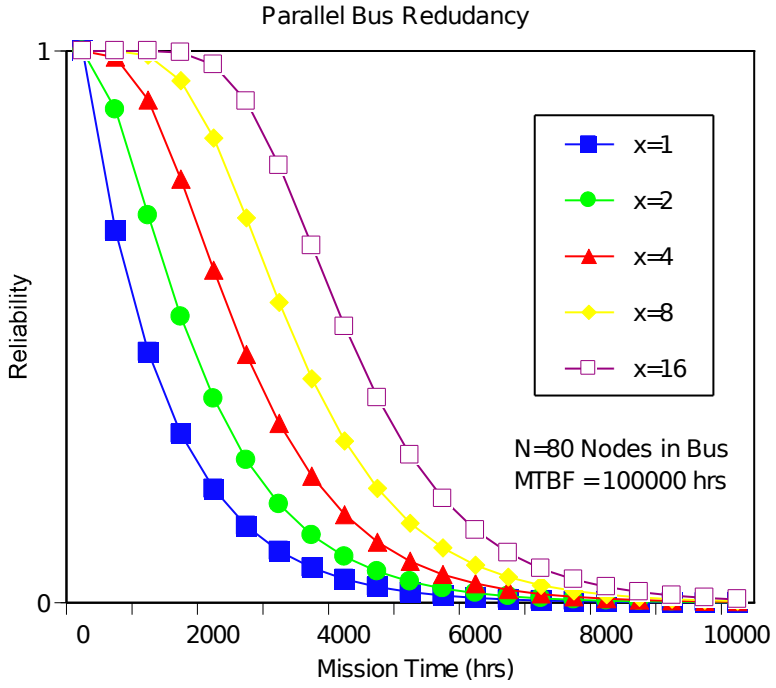


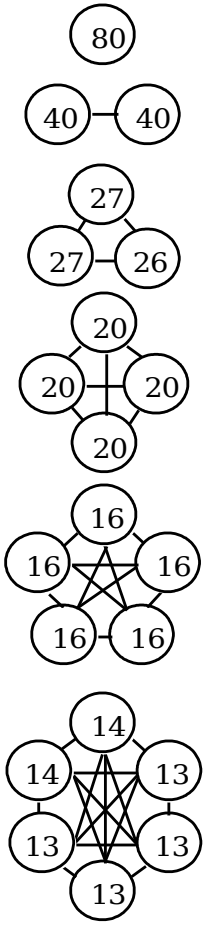
xN+ m Redundancy

xN Redundancy:
80 node bus:



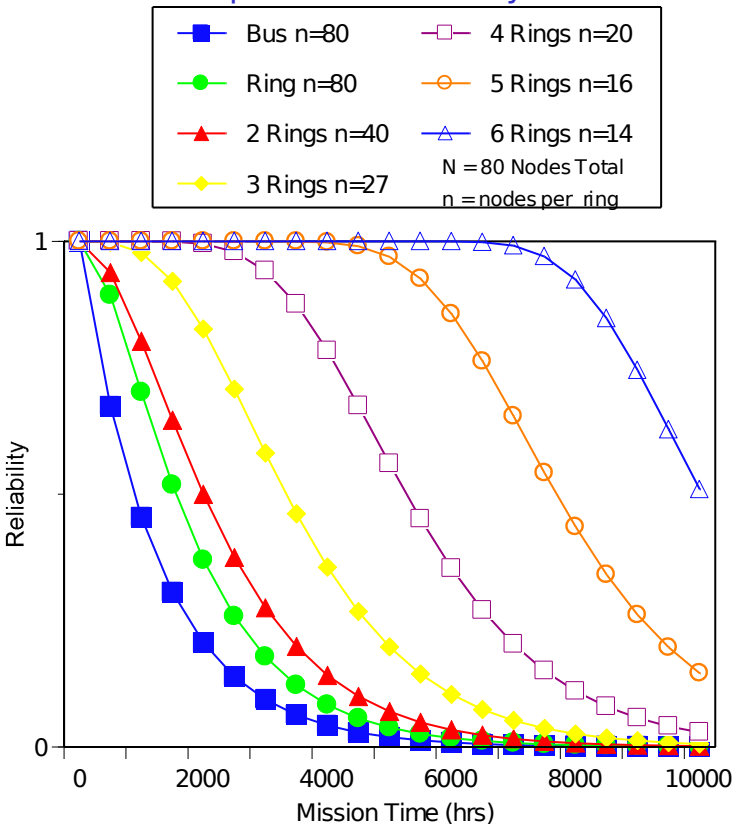
Exponential increase in hardware:
x = 2, 4, 8, 16. (x copies of N nodes)
Linear increase in Reliability





xN+ m Redundancy:
80 Nodes partial mesh of channels

Fractional increase in hardware:
m = 1, 3, 6, ... (m redundant routers)
Exponential increase in Reliability
Enables optimized reliability vs. cost



Critical Enabling Technology

- Baseline Technology

  LonTalk (ANSI 709.1 & ANSI 852) - de-facto open COTS standard

  COTS limitations for survivability
  - Neuron chip only 8-bit
  - No domestic open implementations
  - Topology not reconfigurable
  - No design & management tools for survivability
- Adept's Innovations
  - High performance software (C) & firmware (VHDL) implementations of ANSI 709.1 protocol (LonTalk) and ANSI 852 with QOS
  - LonTalk to IP routers and custom gateways (COTS)
  - Redundant Twin Mode LonTalk to IP routers for high availability applications
  - Commercial market leader in price/performance
  - Next generation lower cost Lon/IP routers in development
  - Affordable, survivable component level automation infra-structure (CLAI) enhancing COTS open standard (ANSI 709.1)
  - Dependable topology with Network Fragment Healing (NFH)
  - Supported software design & management tools
  - Derivative network components such as gateways, routers, & sentinels

Features

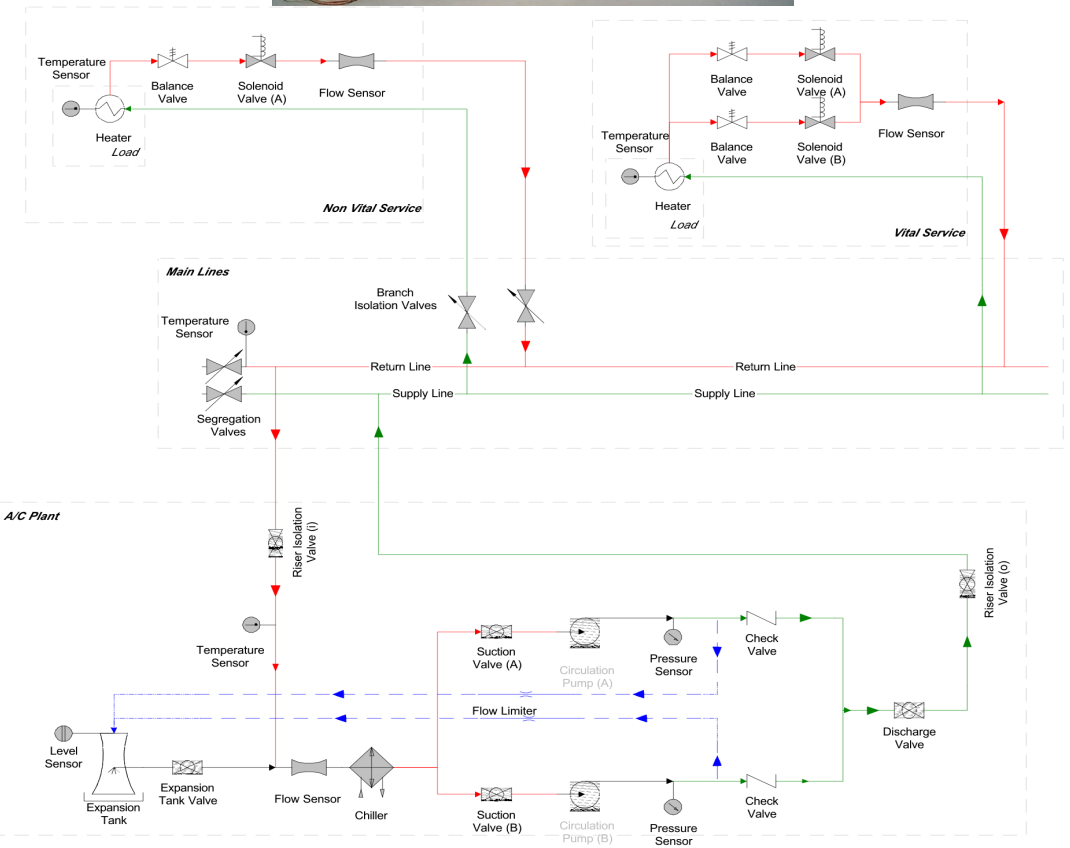
- Cost effective reliable automated systems using a scalable reconfigurable xN + M redundant architecture
- Architecture Elements
  - Distributed intelligence: from the component level on up
    - Supervisory control with local autonomy in the event of fragmentation
    - Local intelligence provides enhanced survivability through local situation awareness and conditional response/behaviors
  - Dependable partial mesh of channels topology
  - Network fragment healing
    - Fine-grained online reconfiguration capability
    - Supporting electronics
  - Network design, installation, configuration, & management tools
  - Network pre-hit configuration tools
  - Complementary survivable reconfigurable networked power system

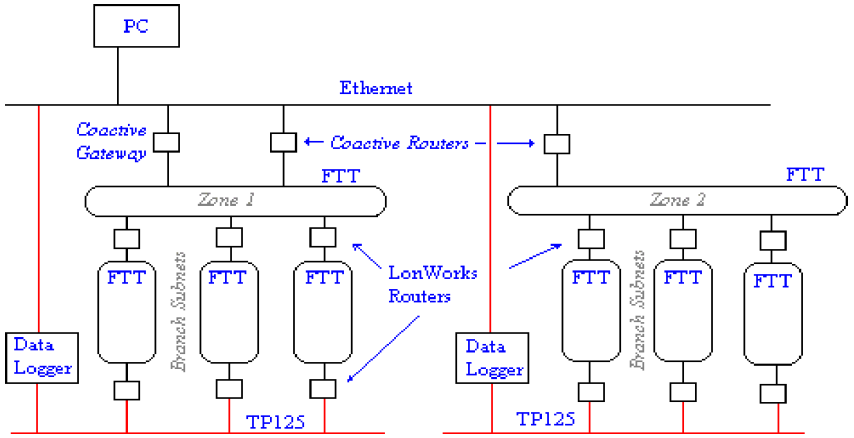
Evaluation of Network Survivability

Example Projects

Demonstrator
NSWC/CD Philadelphia

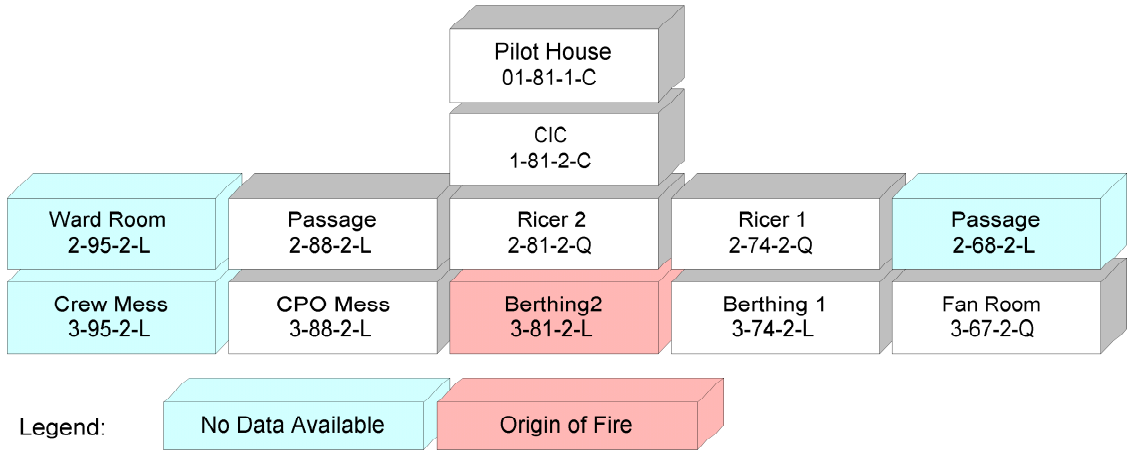
- Reduced scale DDG-51 Chill-water plant
- Distributed event driven control logic
- 200+ nodes
- Automated COTS valves, pumps, chillers, sensors
- Immersion heaters simulate loads
- LonTalk based
- Adept developed network architecture and designed and programmed node software

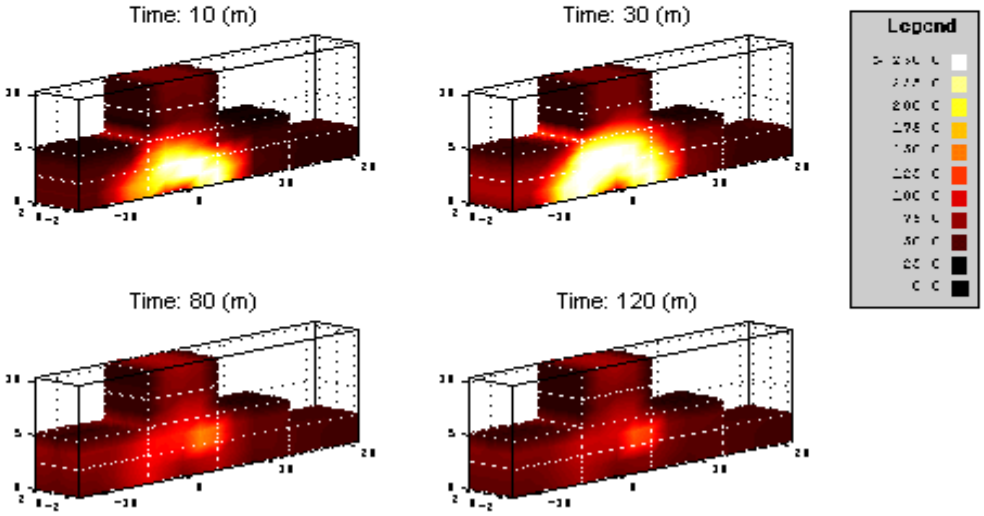


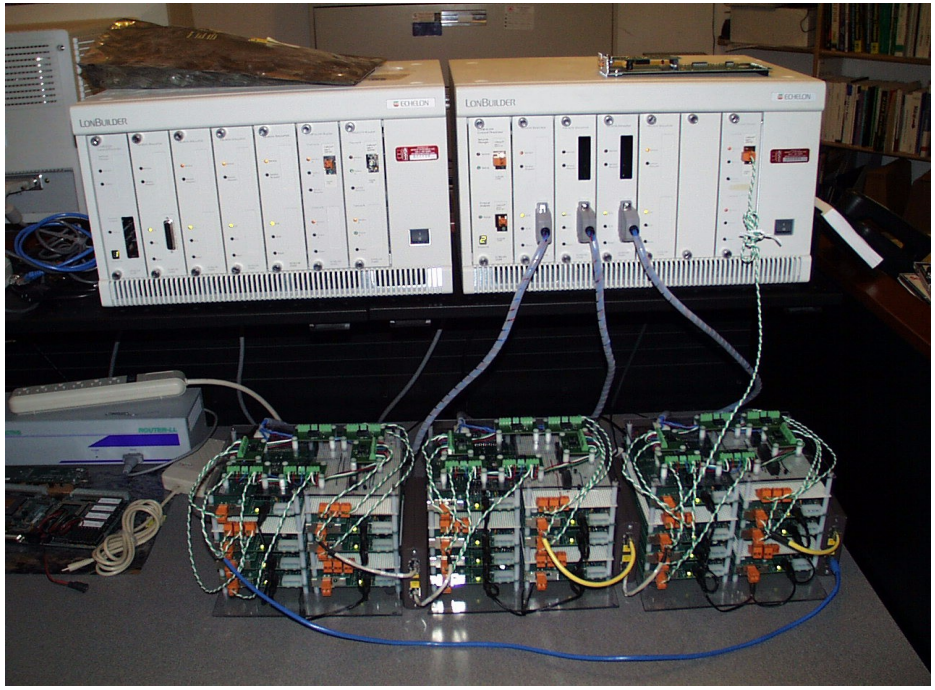


DC-ARM USS Shadwell

- Distributed computation for fire spread model
- Sent to nodes via network
- Timestamp allows nodes to determine the time elapsed at a given influence

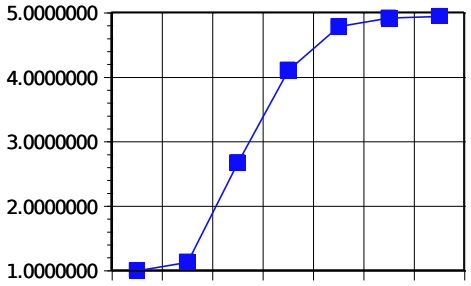


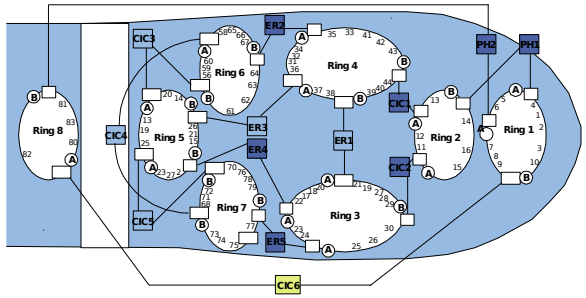




Network Fragment Healing - ONR Afloat Lab

Survivability = Susceptibility, Vulnerability, Recoverability
NFH enhances recoverability and decreases vulnerability

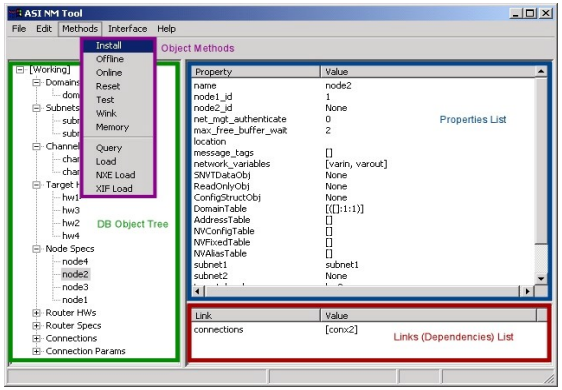


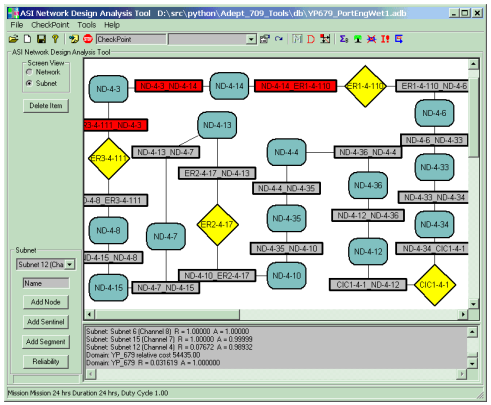


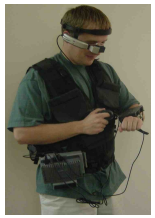
Program Elements
- Adept Systems Inc (NFH, Automation Technology)
- Anteon Corp. (Systems Integration, Operations)
- NSWC (HMI, Controls)

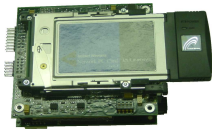
Investment
- 5+ Million over 1999 - 2002

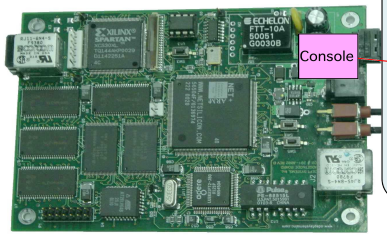
Research, Test, and Demonstration Projects
- Component Level Automation Infrastructure
- Component Level Intelligent Distributed Control Systems
- Network Fragment Healing + Dependable Topologies
- Network Management Tools
- Survivable Automation System Design Tools
- Automation Electronics
- Distributed Monitoring and Control
- Reconfigurable Electrical Systems
- Pre-hit Configuration

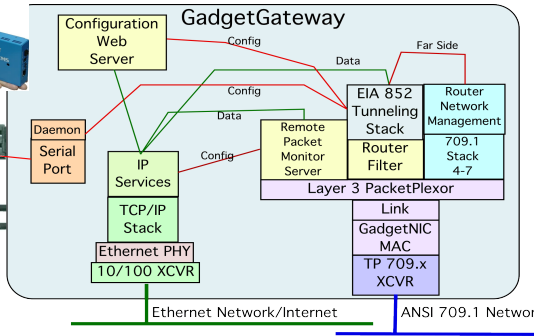




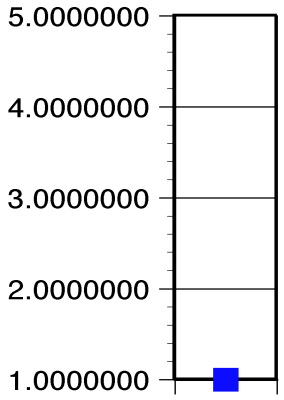


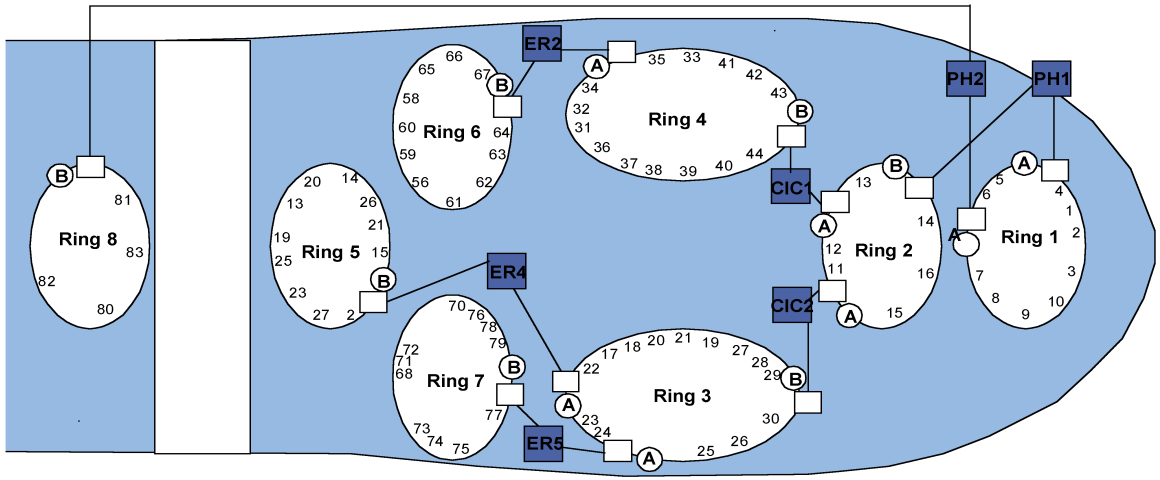


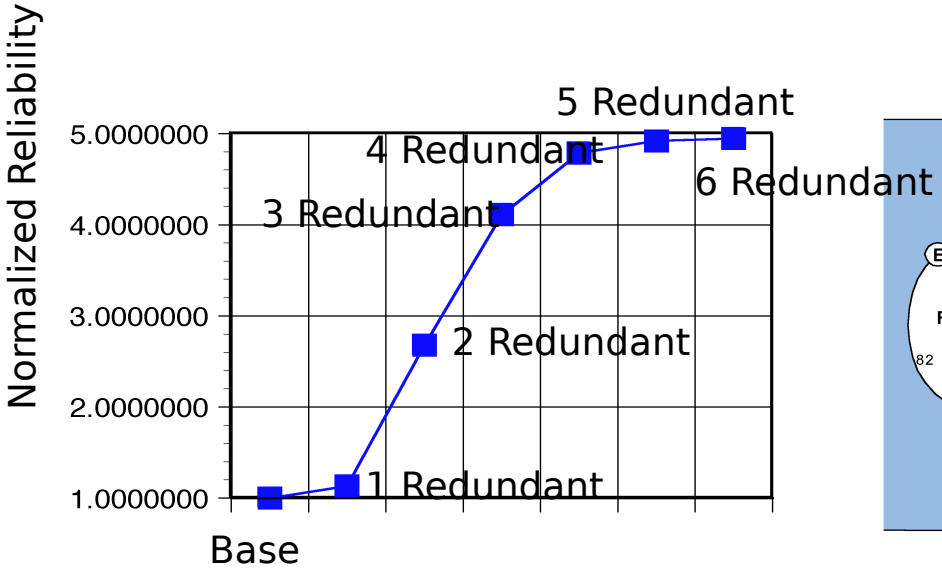


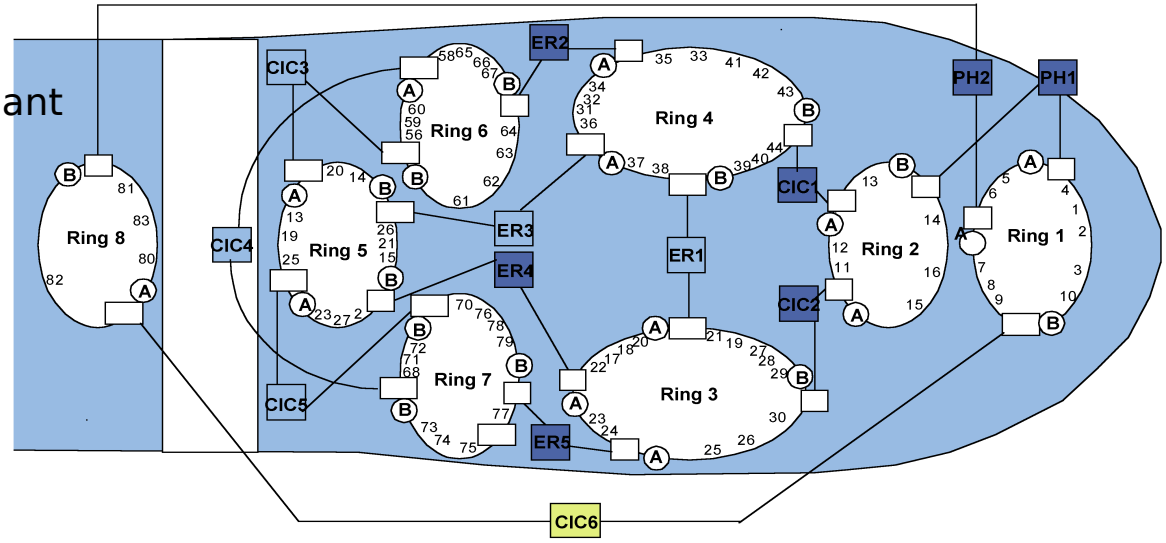


Example Analysis





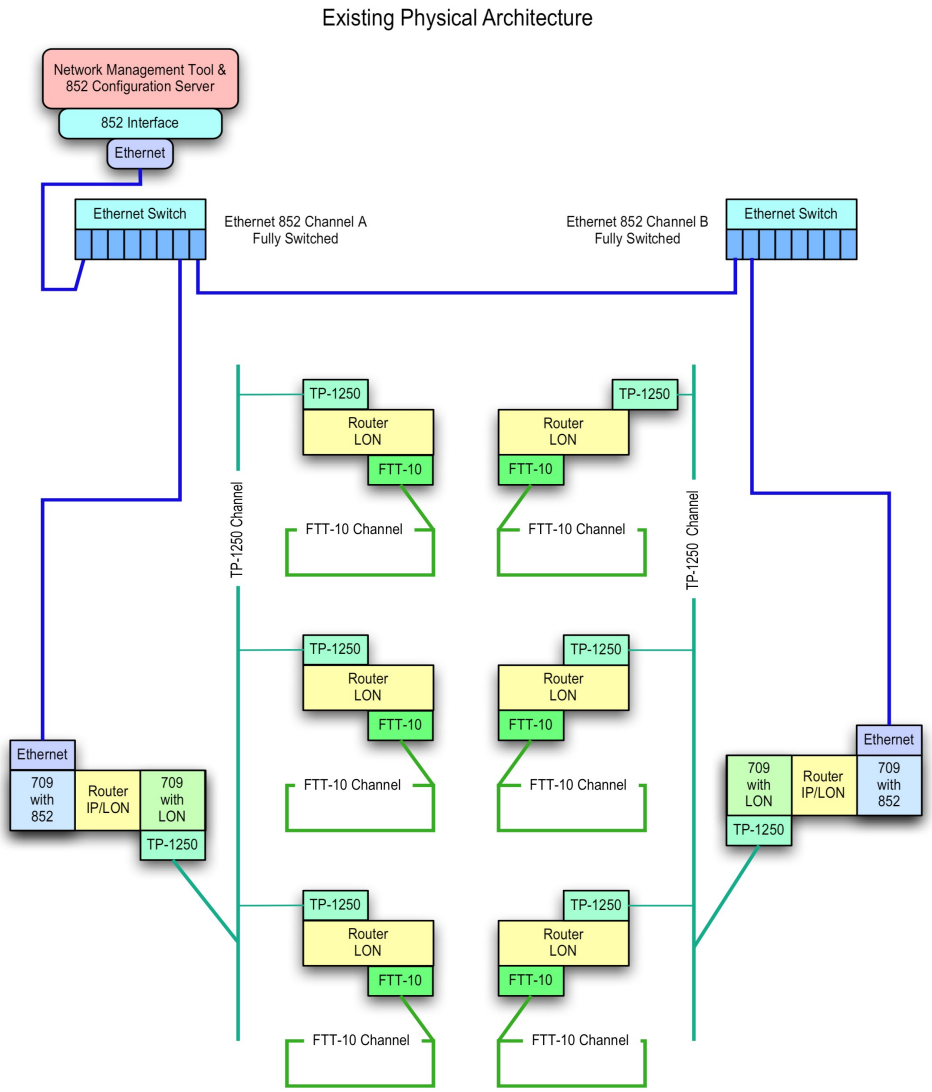




Reduction of Single Points of Failure ex USS Peterson AFSS Testing

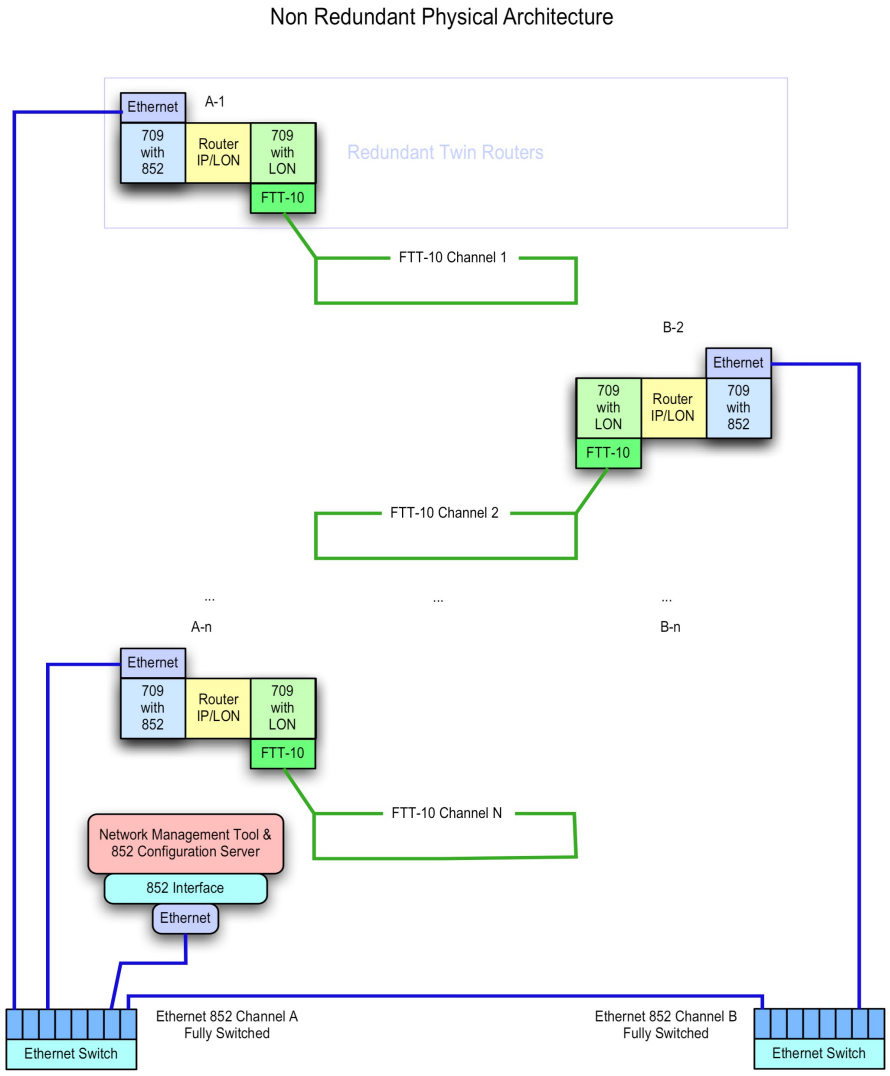
Existing Architecture

- Single point failure vulnerabilities:
  - Ethernet Switches
  - Ethernet Channels
  - LON/IP routers
  - 1250 Channels (short and open)
  - FTT-10 to 1250 routers
  - FTT-10 ring channels (short)



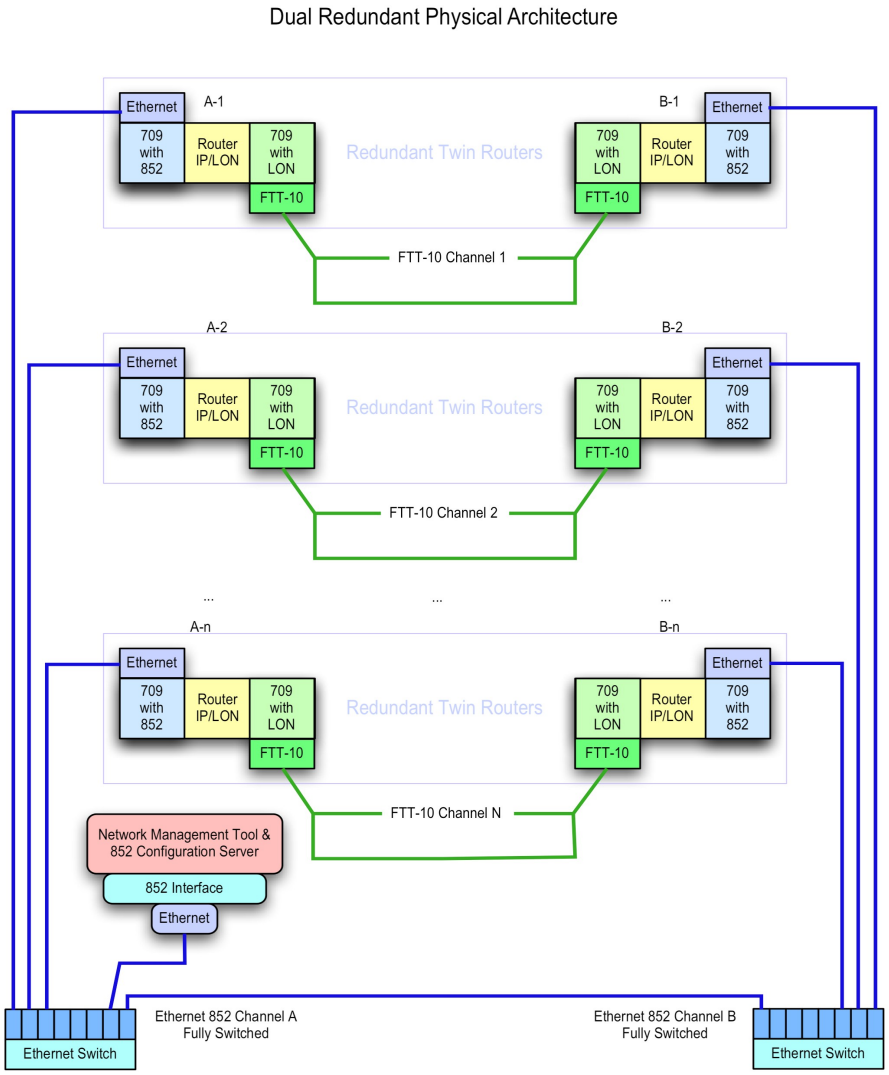
Revised Architecture

- Eliminates single point failure vulnerabilities and cost of 1250 channel and FTT-10 to 1250 routers
- Still vulnerable to single point failures from:
  - Ethernet Switches
  - Ethernet channels
  - LON to IP routers
  - Short on FTT-10 channel



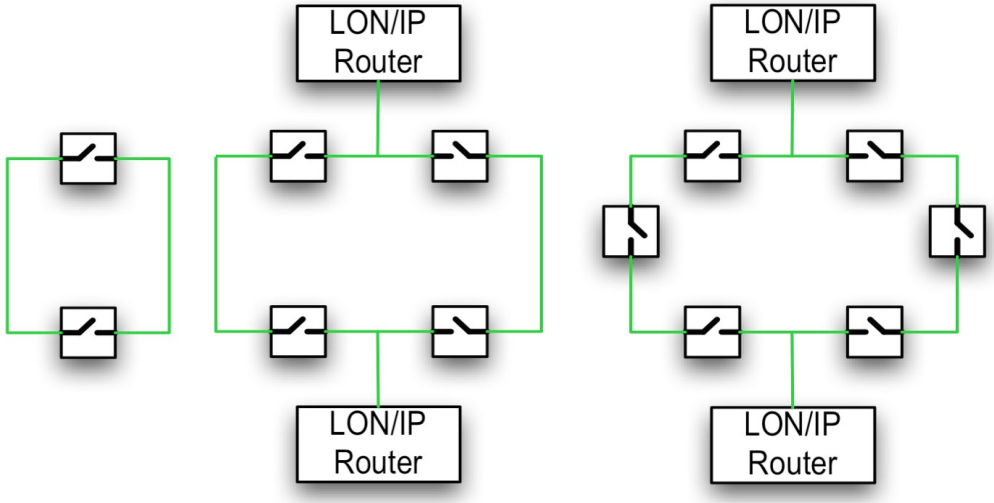
Improved Revised Architecture

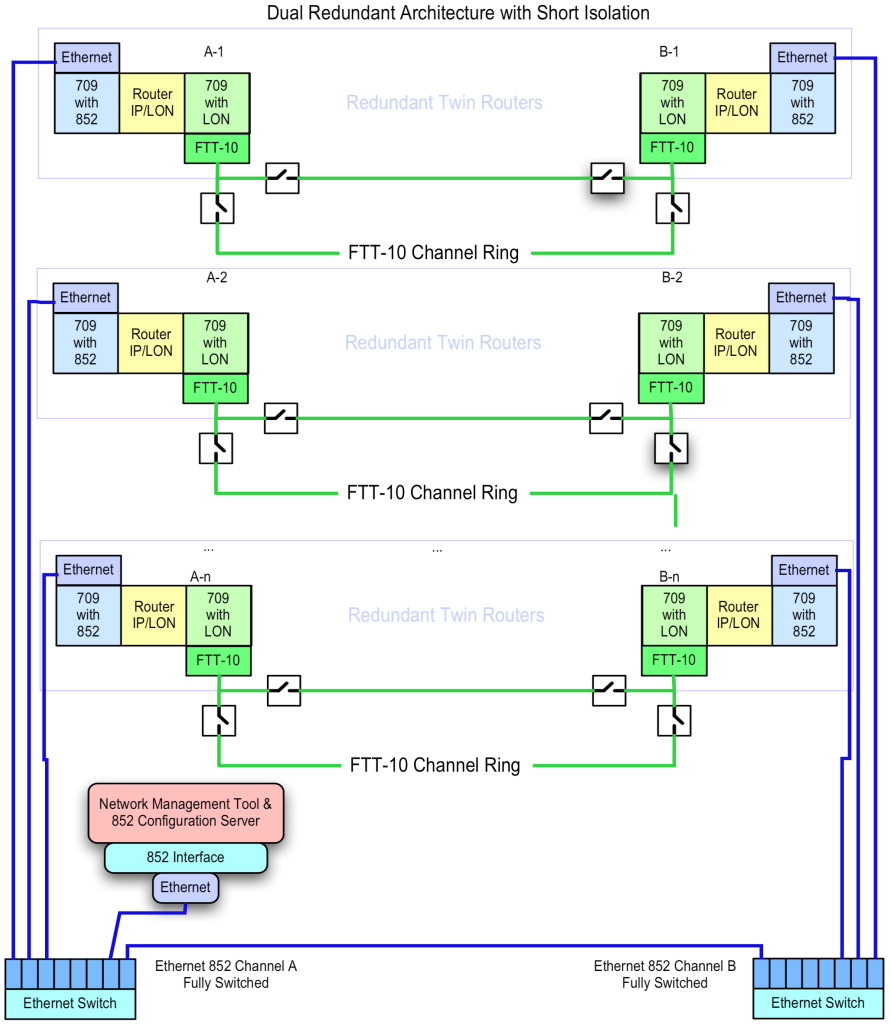
- Dual redundant Ethernet channels with redundant twin mode LON to IP routers
- Eliminates single point failure vulnerabilities:
  - Ethernet switches
  - Ethernet channels
  - Lon to IP routers
- Still vulnerable to single point failures from:
  - Short on FTT-10 channel



Architecture with Short Isolators

- Need 4 isolators or 2 two-sided isolators to isolate one channel and provide half channel protection.
- With only two isolators a failure short of one isolator shorts whole channel
- Two additional isolators provide 3/4 channel protection
- Physical limit on the number of isolators per channel if all active
  - # = termination resistance / line resistance





What's Next for Automation Infrastructures?

Protocols

Algorithms

Architectures

Suitable Automation Infrastructure

1. Scope = ubiquitous.
   - The infrastructure must include everything from the component level up through all the ship's subsystems, systems, operations, and off-ship support.
2. Access = transparent, peer-to-peer, global, & secure.
   - Transparency means that communication over the automation infra-structure's network is invisible to the application, that is, the overhead associated with network use is minimized.
   - The combination of peer-to-peer and global means that any given node can exchange information with any one node if so desired.
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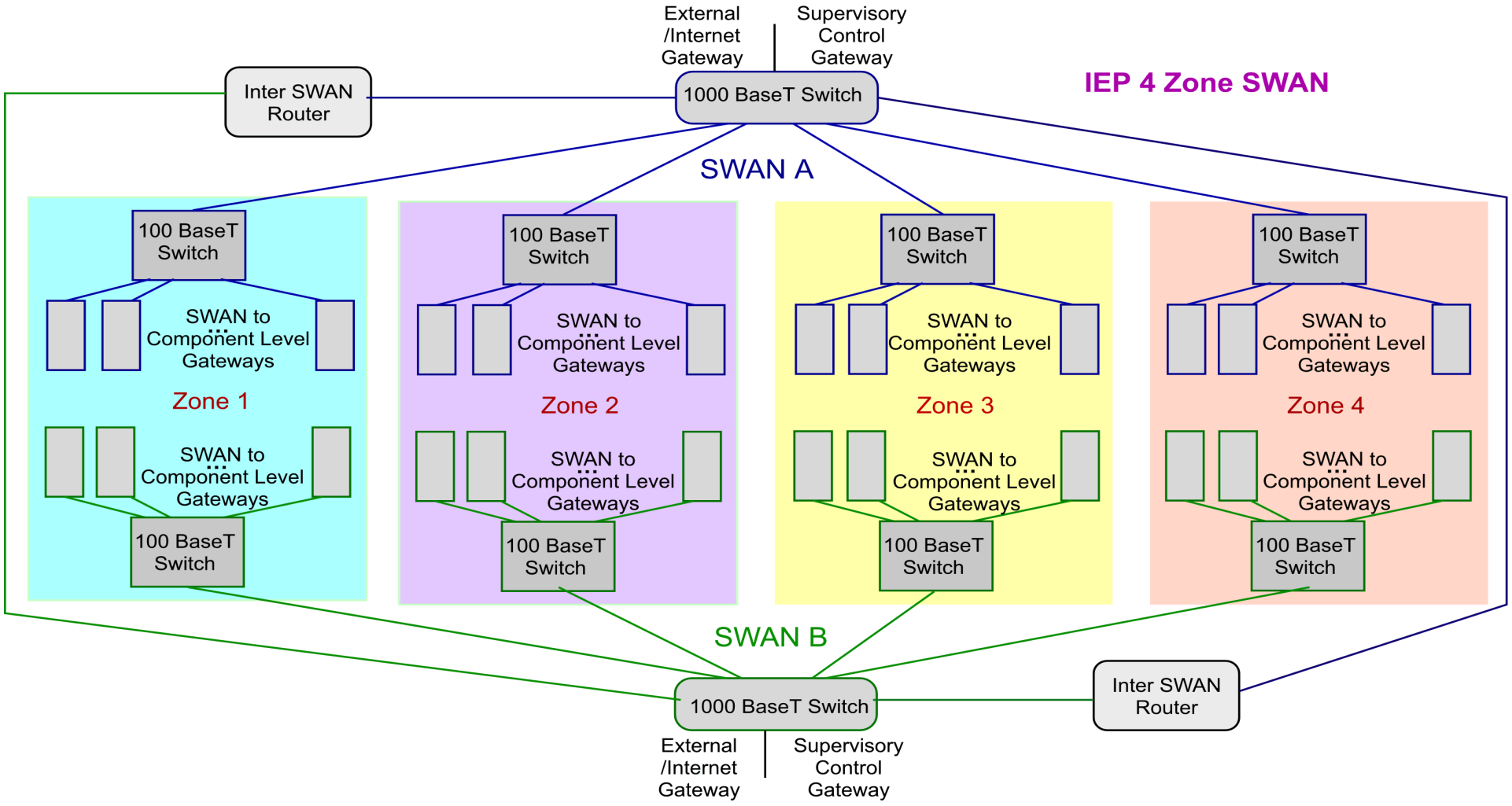
4. Reliability = dependable.
   - Accurate media and network services must be continuously available at acceptable latencies.
5. Cost = affordable.
   - The different attributes must be implemented in a highly cost effective manner. Reduced manning will only come at very high levels of automation with potentially thousands of nodes.
6. Survivability = robust.
   - Must be capable of continued operation at sufficient levels of performance despite damage and casualties induced by stress from shock, blast, fire, and flooding.

Ship Systems Automation Problem

- Current notions of a ship automation infrastructure employ a static tree hierarchy of networks with xN redundancy.
- This approach is inherently non cost effective for survivability.
- Because FireWire supports looping topologies it is the prime candidate for the survivable partial mesh of channels topology for high bandwidth automation applications.
- This means the whole ship automation infrastructure can be put on the same footing for survivability.

Zonal CLAI Architecture



Survivability Constraints of IP/Ethernet

- Conventional 10/100/1000 BaseT Ethernet Uses StarBus Topology = Non-dependable
- Conventional Routed IP/Ethernet Unsuitable for Real-time Applications
  - Uses Spanning Tree Protocol (IEEE 802.1d)
  - Spanning Tree Protocol Slow to Converge
  - MAC address aging in minutes
  - Broadcast storms (entire LAN per segment)
  - Multiple SA-DA problems
  - Poor secure bandwidths for hubs
- Redundant Ethernet Solutions
  - Industrial Ethernet Motivation
  - Redundancy Protocol (RCP-IEEE802.1ac)
    - Not Interoperable
  - Proprietary Switches with Ring Topology Support
    - Interoperable Solutions
    - HyperRing, X-Ring, Turbo-Ring, IRRTP, FRNT
    - Ring capable switch still single point of failure
      - Ring capable switch not always in ring
      - Auto-roll back/restart required

Where to go next

- Adept's approach has so far been limited to the component level and low bandwidth networks.
- A truly low manned ship will require an affordable survivable automation infra-structure at all levels, component, zonal, and ship wide.
- Emerging applications require higher bandwidth for data and sensor fusion tasks.
  - Damage assessment, condition based maintenance, threat assessment, network centric coordination, pre-hit configuration.
- 7 years ago Adept selected what was then the most suitable component level automation technology for cost effective survivability, namely, LonTalk or ANSI 709.1
- Adept has identified a very promising emerging commercially supported automation technology that could provide a complete solution to a suitable total ship automation infrastructure. This new network automation technology is a new standard called FireWireB (IEEE 1394B).

1394B: Next Generation High Speed Wired Media

- IEEE 1394 B
  - High speed
    - 100 Mbps at 100 meters on Cat 5
    - 3.2 Gbps at 100 meters on fiber
  - Low Cost
    - XCVR and Chip < $10 10/100 Ethernet)
    - Leverages installed base of Ethernet cat 5 and fiber cabling (8b/10b coding)
  - Large COTS market momentum
    - Millions of B devices fielded, 20% annual growth rate
    - Automobiles 2006
    - F-35 Joint Strike Fighter Engine Monitoring and Control System, Vehicle Sensors
    - NASA Space Shuttle
  - Asynchronous and Isochronous channels
  - Reliable interconnect and QOS appropriate for control and NFH
  - Looping topology support (rings and looping channels)
  - Protocol agnostic
    - IP tunneling supported (Windows, Linux, and Mac OS X)
    - ANSI 709.1 tunneling can be supported

1394.1, 1394C, 1394.2: Enhancements to FireWire

- IEEE 1394.1 Bridging Spec for Large Networks

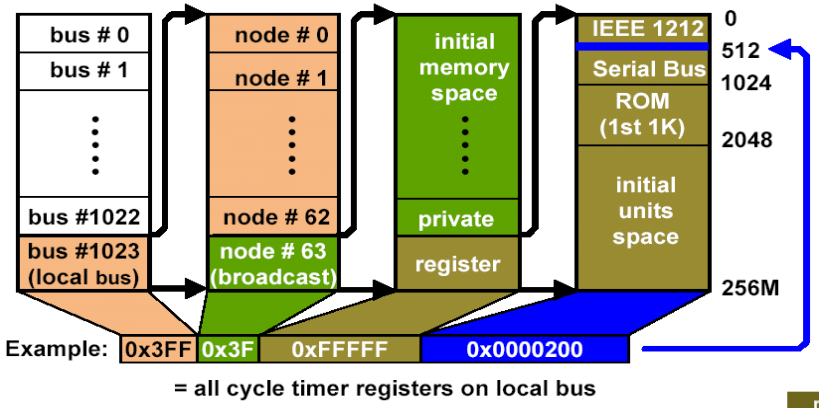
- IEEE 1394 C (FireWire on Gigabit Ethernet)
  - 1000 Mbps Firewire at 100M distance on Cat 5e
  - Auto negotiate FireWire or Gigabit Ethernet on same RJ45 connection
  - Spec finished, chips in development

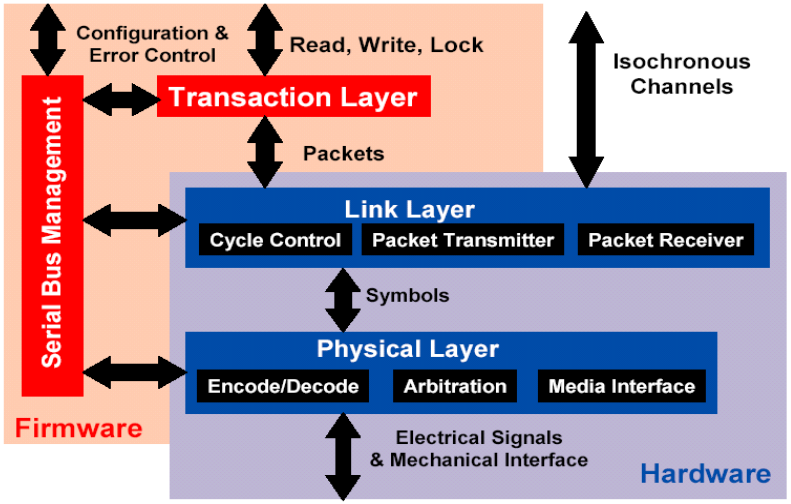
- IEEE 1394.2
  - Adds FireWire type Isochronous Channel to IEEE 1596 SCI (Scalable Coherent Interface)
  - Grid Computing, Supercomputer Clusters
  - SCI is Proposed JSF Unified Avionics Interconnect Standard

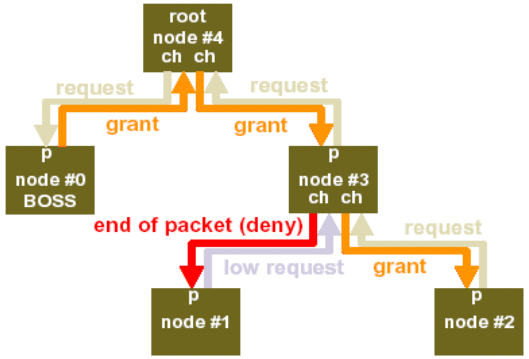
1394 Specifications

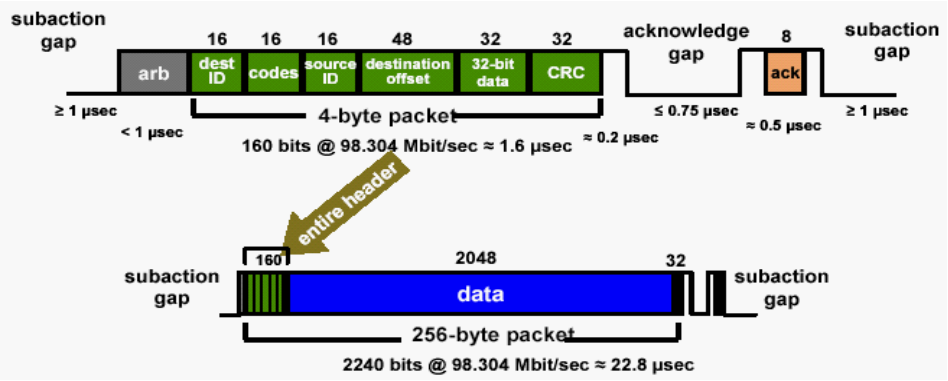
Media	Reach	100 Mbps	200 Mbps	400 Mbps	800 Mbps	1000 Mbps	1.6 Gbps	3.2 Gbps
Shielded Twisted Pair (STP) Data Strobe 1394A	4.5 m	Yes	Yes	Yes	No	No	No	No
Shielded Twisted Pair (STP) 1394B	4.5 m	Yes	Yes	Yes	Yes	No	Yes	Yes
Unshielded twisted pair (UTP-5) 1394B	100 m	Yes	No	No	No	No	No	No
Plastic Optical Fiber (POF) 1394B	100 m	Yes	50 m PDF	New Gen POF	Next Gen POF	No	Nex Gen POF	No
Hard Polymer Clad Fiber (HPCF) 1394B	100 m	Yes	Yes	Yes	Yes	No	Yes	No
50 um Glass Optical Fiber (GOF) 1394B	100 m	Yes	Yes	Yes	Yes	No	Yes	Yes
Unshielded twisted pair (UTP-	100M	Yes	No	No	No	Yes	No	No

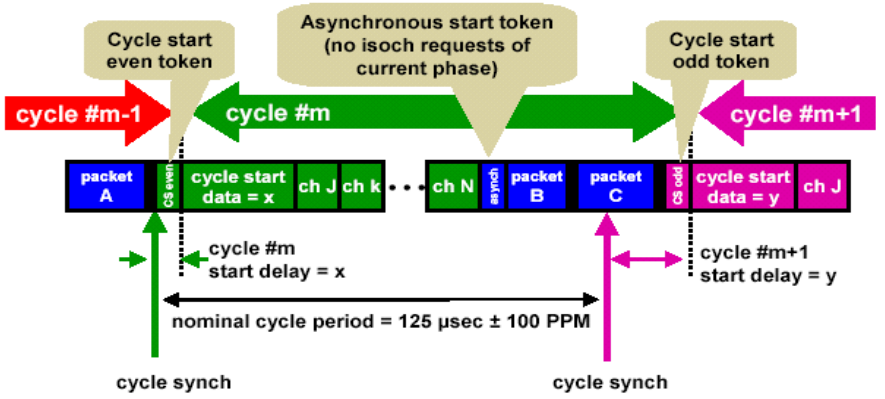
1394 Architecture







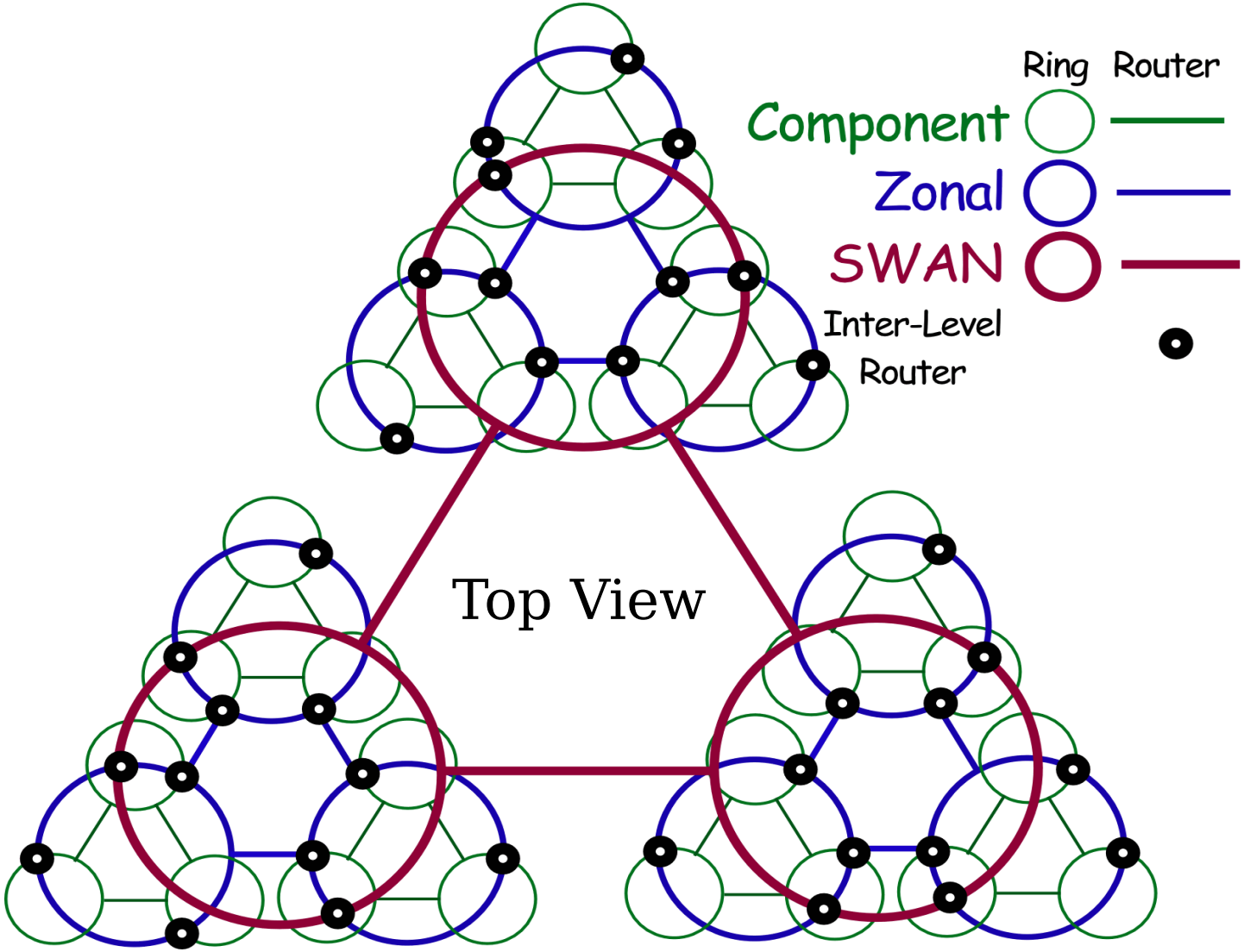




FireWire Research Issues

- Industrial automation applications still immature
  - Primarily vision systems
  - IIC (Instrument and Industrial Control) Spec Draft
  - Need devices interfaces & gateways to non-IP legacy systems
- Scalability
  - Channel limited to 64 nodes.
  - Large networks require 1394.1 Bridges
  - Need to add network fragment healing support to 1394.1 Bridges
- DD(x) and TSCE Integration
  - RTPS and DDS interface
  - Sensor IEEE 1451 interface

Future Survivable Hierarchical System Automation Architecture



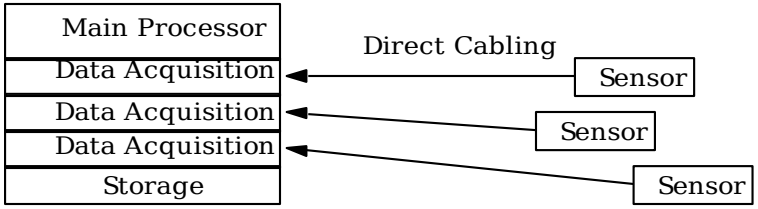
Partial Mesh of Channels = Dependable Topology

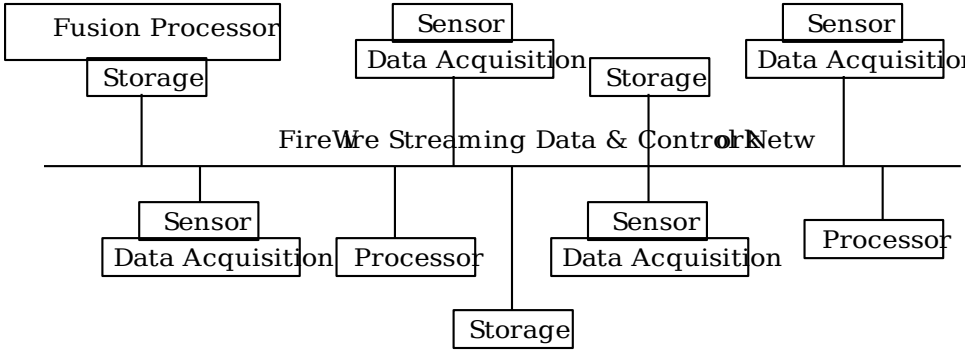
Survivable Distributed Data Fusion Hardware System Architecture for Situational Awareness & Damage Control

Current approaches are usually centralized, non-scalable, non-survivable

Future approach uses fully distributed data acquisition,storage, fusion, and control based on high bandwidth 1394B,C.

Most scalable, most survivable, most efficient use of resources.





Advantages

- Enables the same degree of reconfigurability and flexibility for systems integration with high bandwidth devices as is now achieved with low bandwidth devices.
- More efficient unified architecture. Multiple protocols tunneled over one cable and one XCVR per node.
- Bus powered devices = low power devices need no additional cabling. System capability can be scaled more easily as devices can be attached to the bus.
- System integration is simplified as only one network interface or peripheral interconnect standard is needed.
- Leverages inexpensive COTs multi-media components, drivers, & peripherals.

WRADIA: Weightless Reconfigurable Agents for Distributed Intelligent Autonomy

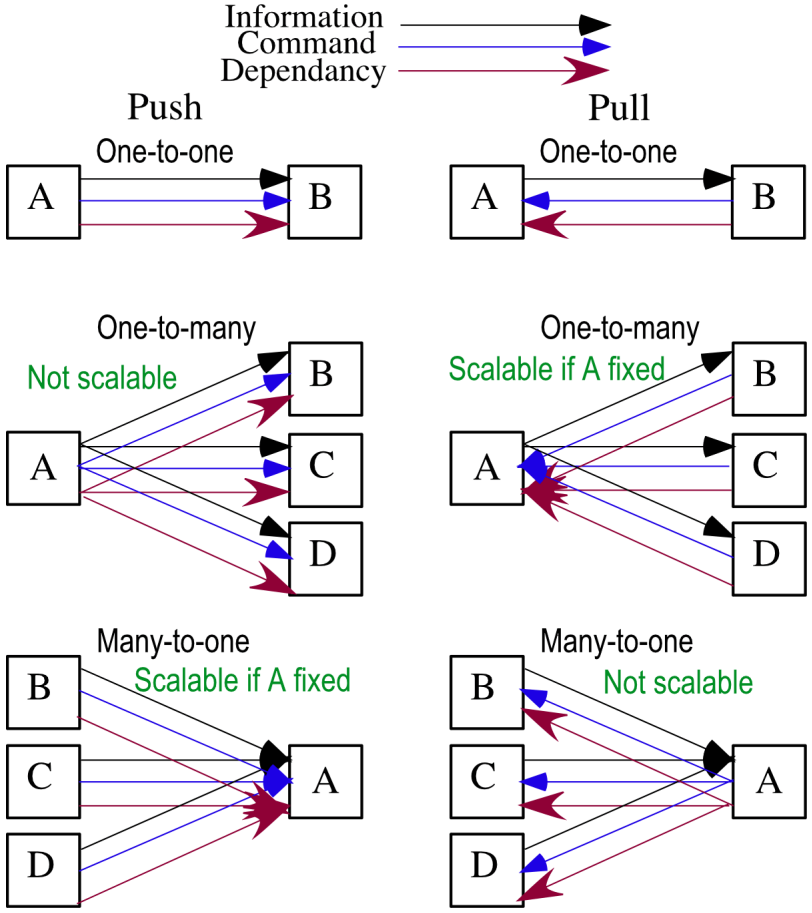
Objectives

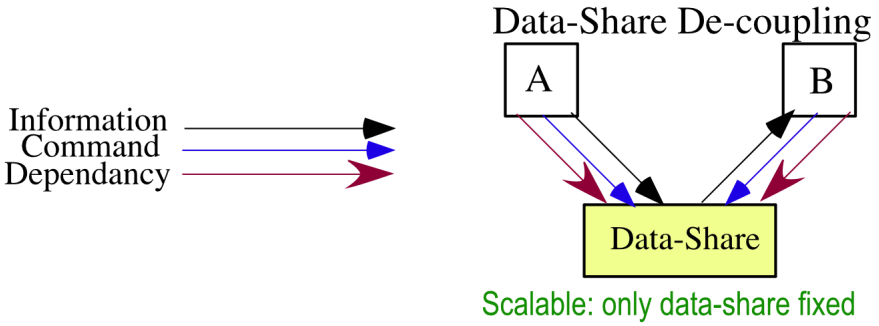
- Dynamic re-planning based on interaction with the environment and in response to unexpected constraints and contingencies
- On board system performance assessment and validation
- Scalable simulation capability
- Synergistic integration of system components
- Convenient human interface for configuration
- Natural expression and representation of both supervisory commands input to agents and situational assessment data output from agents from/to humans
- Multiple agent coordinated operation.

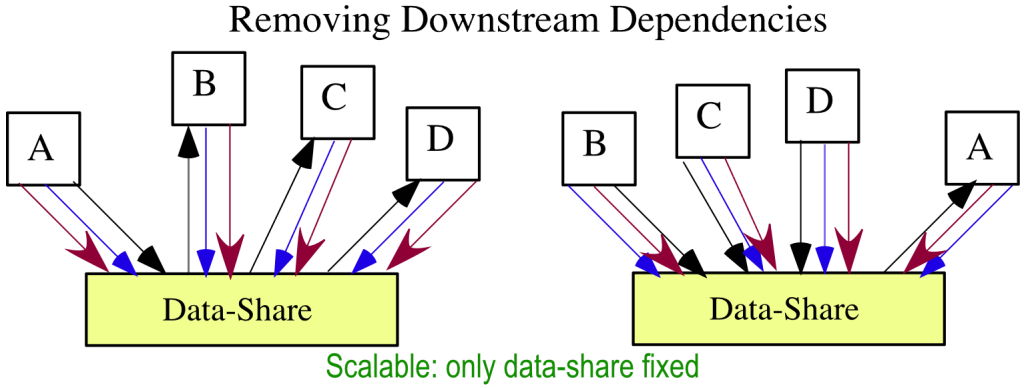
Components

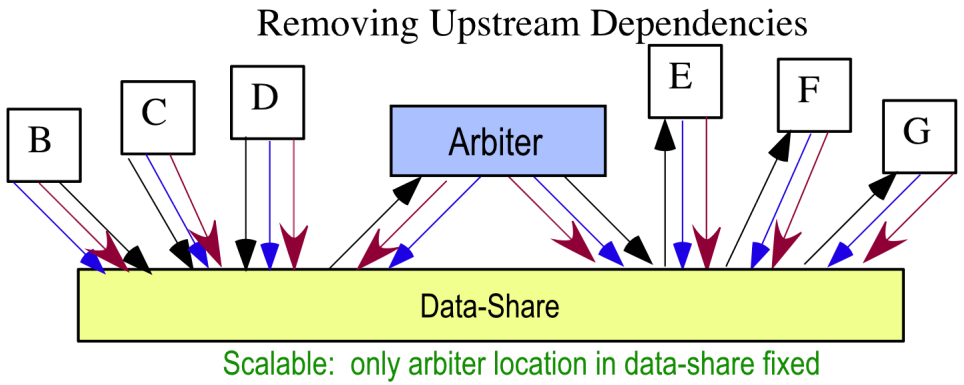
- Reconfigurable component software with hierarchical state machines and data share.
- Symmetric Multi-objective decision making with Elastic Constraint propagation (SMEC) with case based learning
- Weightless autonomous agents using micro-threads
- Python development environment.
- Pattern Centric Reasoning for learning and optimization

Dependency Reduction

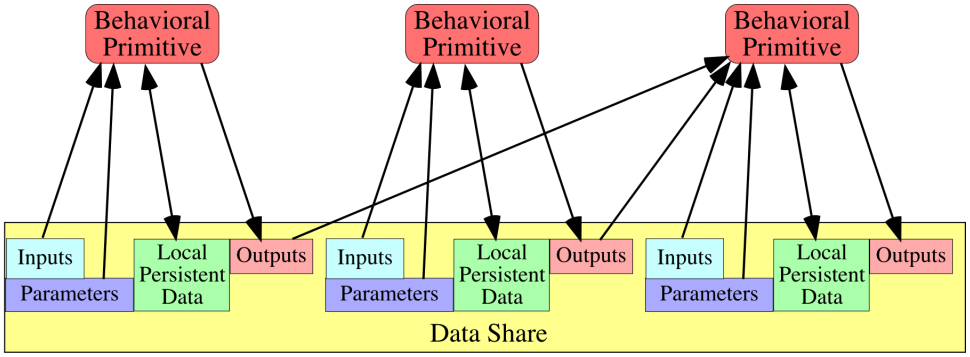


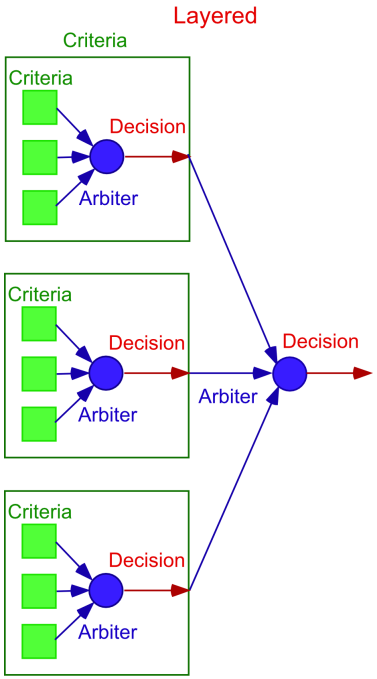


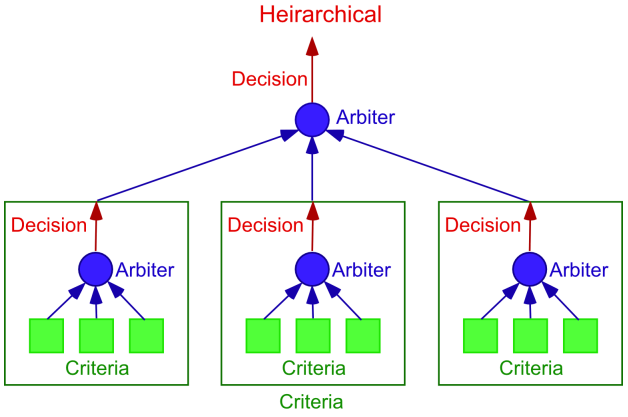


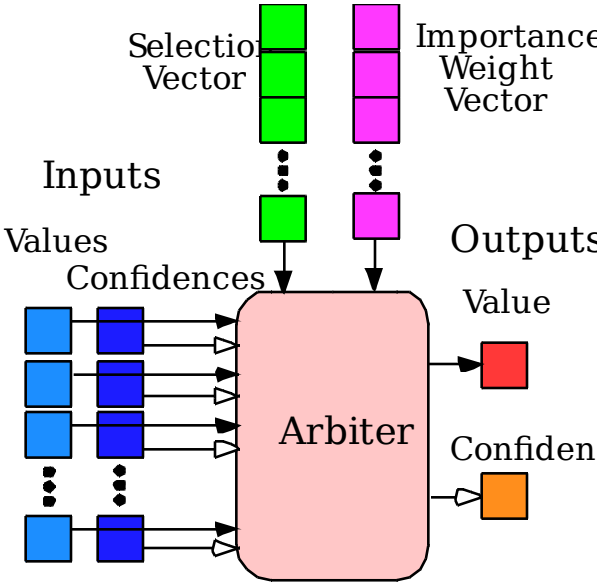


Behaviors and Behavior Fusion

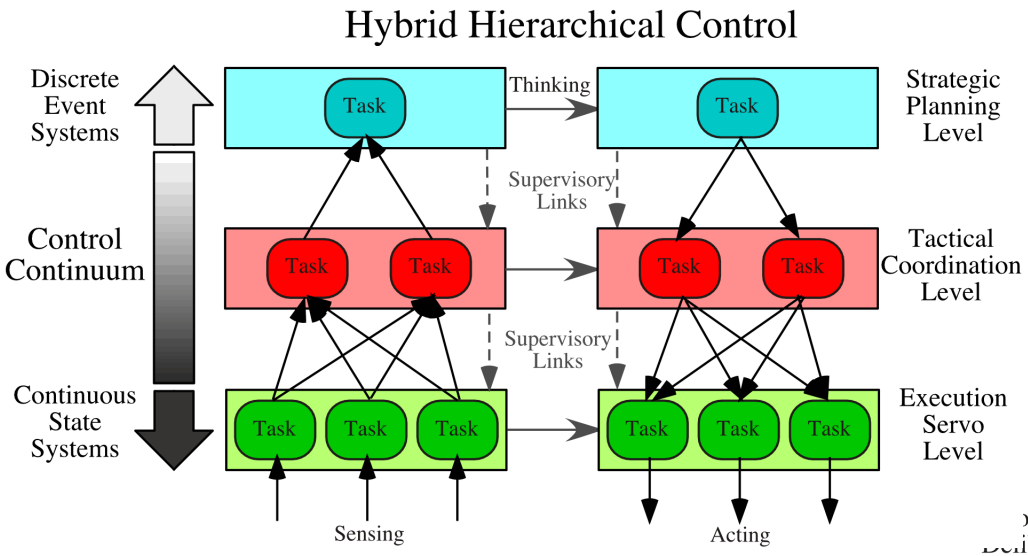


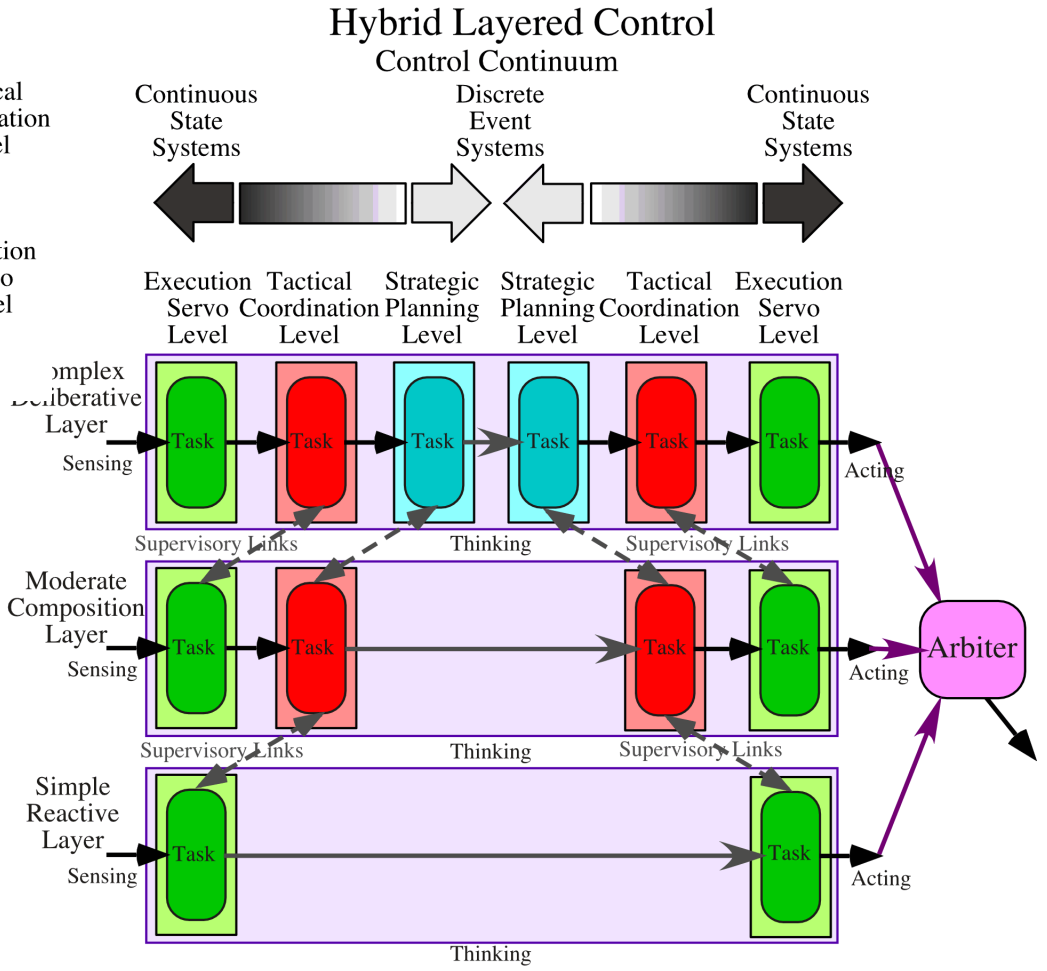




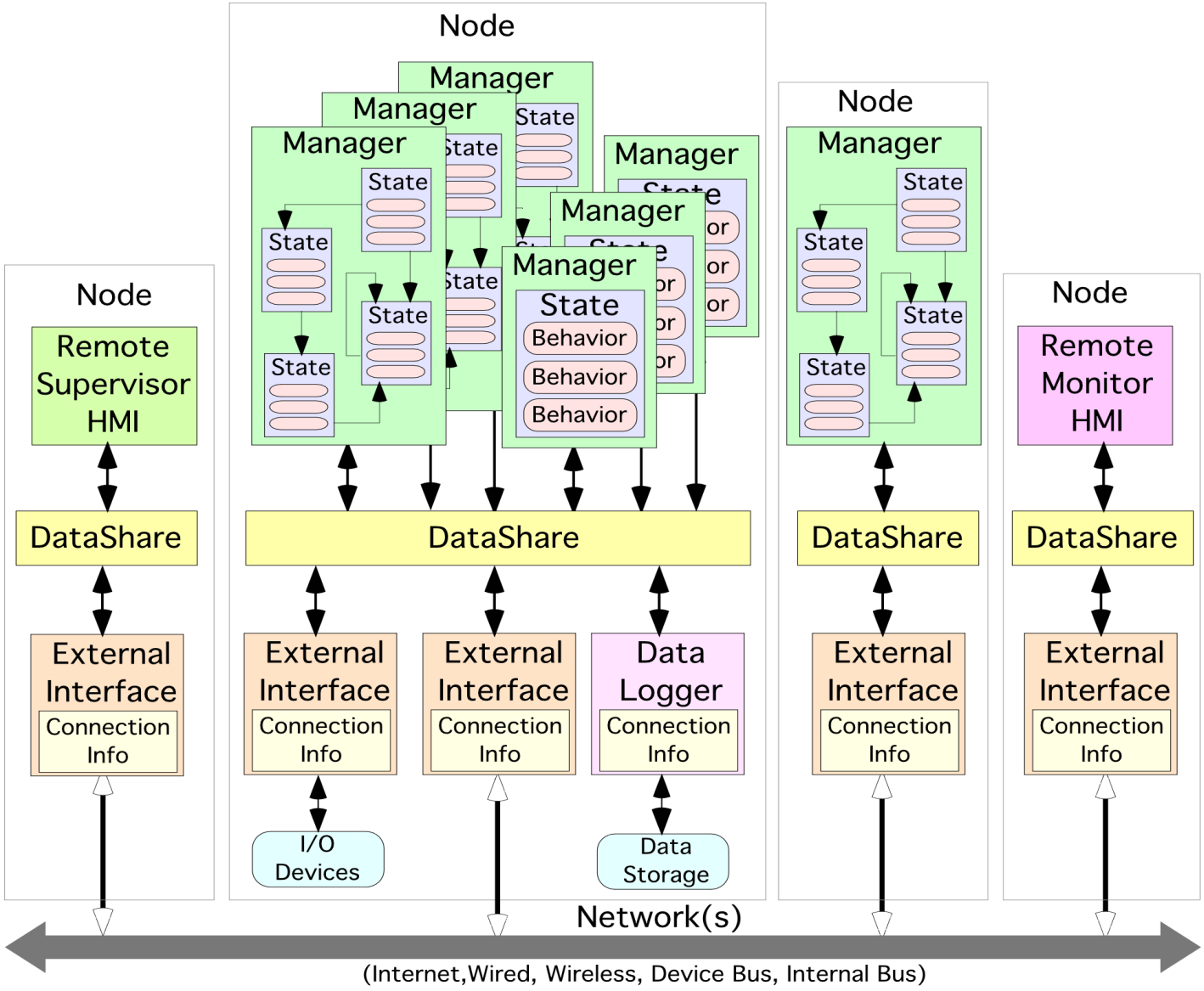


Control Architecture Convergence



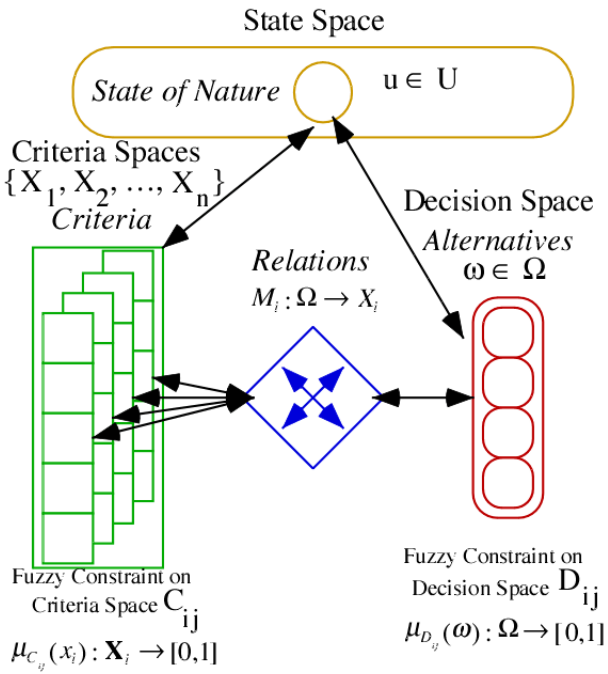


Component Software Architecture



SMEC

Symmetric: Both goals and constraints are expressed with fuzzy sets.
Decision-making consists of finding the confluence of goals and constraints by aggregating the respective fuzzy sets



state of nature $u \in \mathbf{U}$ state space

decision alternative $\omega \in \Omega$ decison space

set of criteria $\mathbf{C}$ defined on $\mathbf{X} = \{X_1, \ldots, X_m\}$ criteria spaces

fuzzy constraint $C_{ij} = j^{th}$ constraint on i^{th} criteria space

membership function $\mu_{C_{ij}}(x_i) : \mathbf{X}_i \rightarrow [0,1]$

$M_i : \Omega \rightarrow X_i$ relation between decision space and i^{th} criteria space

C_{ij} induces a constraint D_{ij} on Ω through M

If $M_i \equiv m_i(\omega) \quad s.t. \quad x_i = m_i(\omega)$ Then

$\mu_{D_{ij}}(\omega) = \mu_{C_{ij}}(x_i) = \mu_{C_{ij}}(m_i(\omega)) \quad \forall \omega \in \Omega$

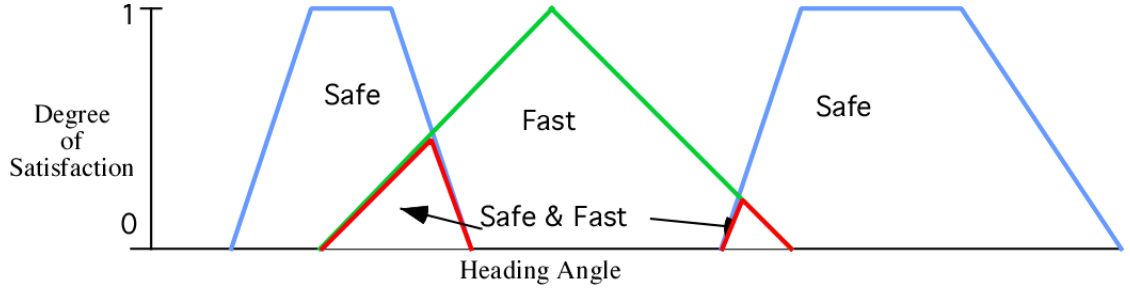
$\mu_{D_{ij}}(\omega) : \Omega \rightarrow [0,1] \quad \mu_{C_{ij}}(x_i) : \mathbf{X}_i \rightarrow [0,1]$

Final decision by aggregating constraints

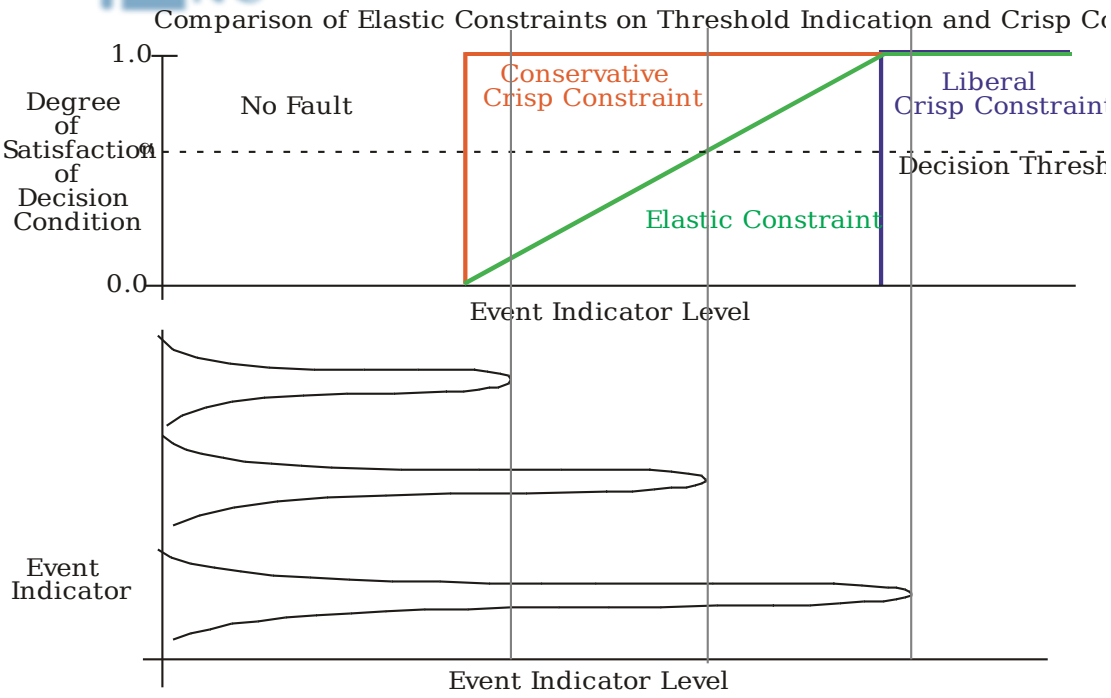
$\mu_D(\omega) = Agg(\mu_{D_{11}}(\omega), \mu_{D_{12}}(\omega), \ldots, \mu_{D_{21}}(\omega), \ldots, \mu_{D_{mn}}(\omega))$

Objective: get there fast and safe

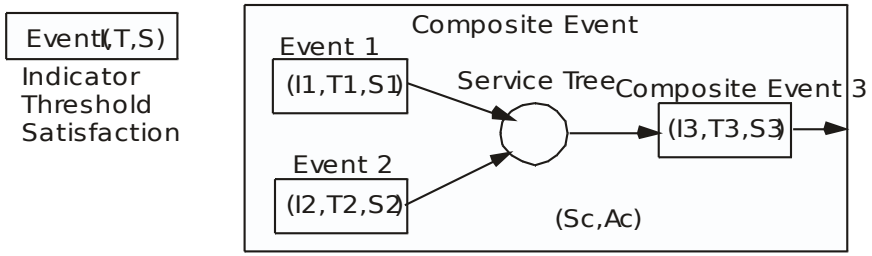
Constraints: obstacles dead ahead and to sides, slower paths on bigger turns



Elastic Constraints



- Crisp Constraint Sensitive to Threshold (Brittle)
- Postponing Thresholding Until End of Logic Processing is More Robust (Smooth)
- Elastic Threshold Can be Raised/Lowered to Reflect Risk
- Adaptive Threshold Estimation Can Track Time Varying Conditions

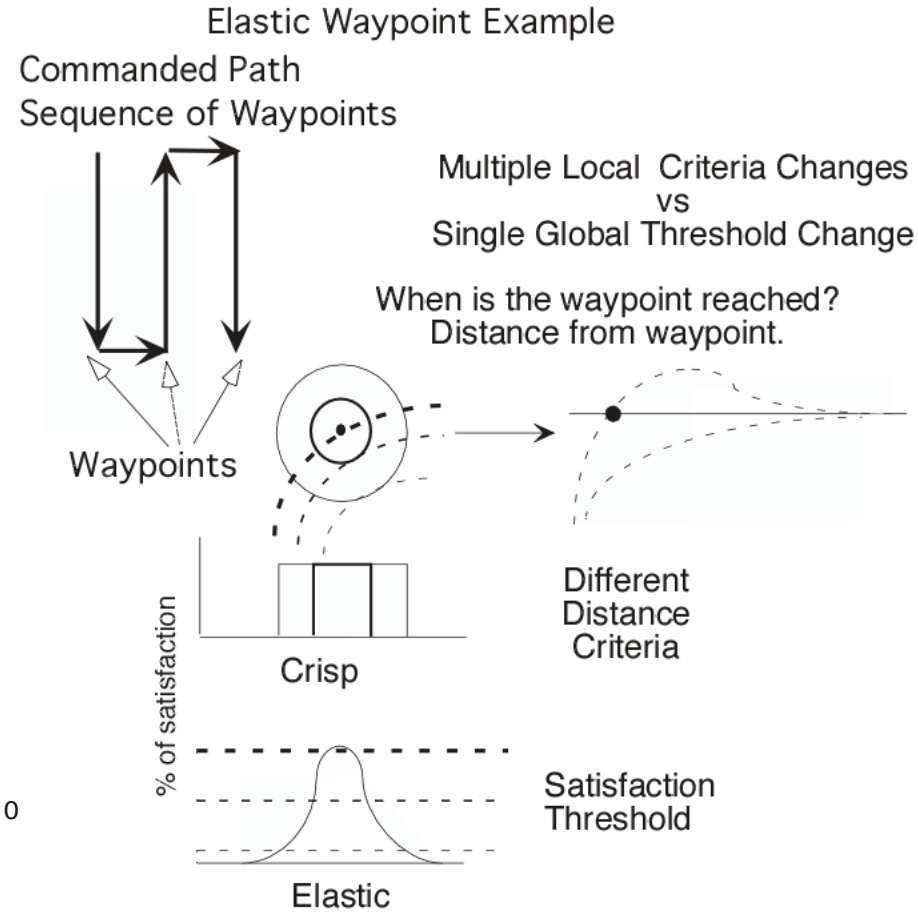


Boolean Composition Logic
((I1 >T1) AND (I2 >T2)) OR (I3 >T3) THEN Event

=4T1=5,I2=3T2=7,I3=2T3=3
ent = FALSE

Elastic Composition Logic
Sc = MAX(S3,MIN(S1,S2))
IF Sc >Ac THEN Event

I1 ->S1 = 0.9I2 ->S2 = 0.4I3 ->S3 = 0
Sc = MAX(0.7,MIN(0.9,0.4)) = 0.7
Event = TRUE



Weightless Threads

```
#Scheduler
def scheduler(threads):
   for n in xrange(1000):
      for thread in threads:
         thread.next()

#Generators as Micro-thread
def thread1():
   while 1:
      #do thread's task here
      yield None

def thread2():
   while 1:
      #do thread's task here
      yield None

#Execute
threads.append(thread1())
threads.append(thread2())

scheduler(threads)
```

Pattern Centric Reasoning PCR

- Design Pattern: “Each pattern describes a problem which occurs over and over again in our environment, and then describes the core of the solution to that problem, in such a way that you can use this solution a million times over, without ever doing it the same way twice.” (Alexander 77)
  - Pattern description,
  - Problem context, conditions, features
  - Solution elements, relationships, responsibilities, dependencies, implementations
  - Consequences and trade-offs
- CBR is usually constrained to a simple problem structure (feature space) with specific solutions
- PCR is Meta-CBR where patterns are architectures for solutions to a class of problems
- Example: Path planning
  - CBR select from stored paths and reactive obstacle avoidance, to generate new paths
  - PCR select from path planning machine architectures. Parallel evaluation and fusion to generate new paths.
- Trajectory based optimization in Pattern or Architecture space.
  - Cell Mapping in rule space
  - Each trajectory a WRADIA instance

Summary

- Adept's technology can be efficaciously applied by total systems integrators as a vital part of increased survivability in critical infra-structure systems
- Extra effort in system architecture design
- Keys to solution:
  - Dependable topologies
  - Dynamic reconfiguration of xN + m redundant systems
  - Agent based distributed algorithms
  - Leverage & enhance COTS open standard based systems